What systems request a beam dump?

J. Wenninger, CERN, Geneva

Abstract

The protection system for LHC beam operation is composed of 'client systems' that may request beam dumps, of a beam interlock system that transmits the requests and of a beam dumping system that extracts the beams to the beam dump blocks. The various players involved in beam interlocking will be presented, and the core systems that are required before beam operation may start will be highlighted. Possibilities to stage some of the systems during the commissioning phase will be discussed. Diagnostics and controls requirements will be presented.

INTRODUCTION

Key parameters for machine protection are the beam energy, beam intensity and beam emittance that influence the stored energy and energy density, the minimum β^* that influences collimation and failures and finally the beam intensity from the SPS that influences the stored energy at injection. The stored energy (density) alone is not the whole story, since the failure mechanisms play also an important role for damages through impact angles and time constants.

Safe beams

The TT40 damage test presented by V. Kain at Chamonix 2005 [1] indicates that the melting point of Copper is reached at the peak of the shower for an impacting beam intensity of 2.5×10^{12} protons, see Figure 1. This result is valid for an impact orthogonal to the target surface. The test results agree with estimates based on FLUKA simulations.

Based on those results the MPWG has adopted for the LHC a limit for the safe beams 450 GeV of 10^{12} protons with nominal emittance.

FLUKA simulations indicate that the peak energy density in the shower scales with $1/\sigma$, with σ the r.m.s. beam size. The energy dependance of the peak energy density that is relevant for damage scales with $E_{beam}^{1.7}$, this scaling includes the effect of the emittance reduction with energy. Based on this scaling law the damage limit at 7 TeV corresponds to 1% of the damage limit at 0.45 TeV. Scaling the safe beam limit given above to 7 TeV yields therefore a limit for safe beams of 10^{10} protons at 7 TeV.

The pilot bunch with nominal emittance is therefore close to the damage limit (within a factor 2-4). A pilot bunch with a reduced emittance of ε^* = 1 μm is therefore at the damage limit!

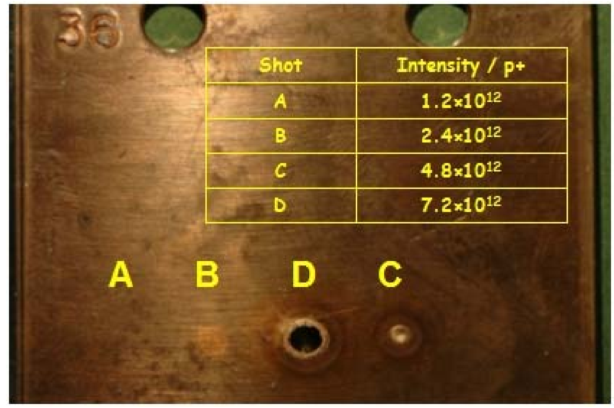

Figure 1: Damage due to beam impact on a Cu plate near the maximum of the shower from a 450 GeV proton beam. The four impacts with different intensity are marked A,B,C and D. The beam intensities are indicated.

The present recommendation of the MPWG is to consider that for a nominal emittance, a pilot **should** be safe at 7 TeV. However

- the safety margin for some failure scenarios is marginal,
- there are uncertainties in scaling the simulation,
- the damage levels of materials other than Cu are not (yet) well known,

therefore some protection must be available from the start at 7 TeV even for a pilot bunch, in particular because operation with low intensity expected to last for a short time.

It is important to note that the damage limit also depends on the failure mode and on the beam impact angle which makes the picture even more complicated.

MACHINE PROTECTION COMMISSIONING

The client inputs to the Beam Interlock System that are required for machine protection as a function of the machine commissioning stage are presented in Figures 2 and 3 for injection and top energy. The color coding of the tables is:

- Grey : input is not required
- Green : input is not required, but expected to be operational or in a commissioning / test phase.

System	Commissioning before beam possible ?	First pilot beam	10^12	43 bunches 1.7 10^12	156 bunches 6 10^12<N<1.4 10^13	936 bunches >5 10^13
Powering interlock system	YES					
Beam interlock system	YES					
Safe distribution of energy	YES					
Safe beam flag	PARTIAL					
Beam presence flag	PARTIAL					
Safe distribution of mode	YES					
Safe distr. of squeezing factor	PARTIAL					
Beam interlocks SPS to LHC	YES					
Injection protection	NO					
Access system	YES					
Vacuum system	YES					
Magnet current change monitor	YES					
BLMs, collimators & apertures	PARTIAL					
BLM in the arcs	PARTIAL					
Collimators and beam absorbers	NO					
Beam position change monitors	NO					
Fast beam current decay monitors	NO					
Transverse feedback	NO					
RF	NO					
Experiments	PARTIAL					
Beam Dumping System	PARTIAL					
TCDQ / TCS	NO					
BPM for BDS	NO					

Figure 2: Table of required interlock clients as a function of the machine commissioning stage for injection.

- Red : no beam operation without this input.

For machine protection, the relevant phases are:

- First pilot bunch.
- Beam of 10^{12} protons.
- 43 bunches.
- 156 bunches.
- 936 bunches (75 ns).

From the two figures it is clear that state transitions of the machine protection system appear during commissioning for:

- pilot bunch ramp to 7 TeV : a large fraction of inputs required
- 43 bunch operation ramp to 7 TeV : majority of inputs required
- injection for 156 bunch operation : majority of inputs required

Although the majority of interlock systems must be operational for 43 bunch operation at 7 TeV, the required safety level or complexity is by far not the same as for 2808 bunches. The collimation system is a good example, where only a subset of collimators is required during initial stages [2]. This table is clearly not cast in stone. It is expected to evolute until the LHC starts up.

Software components

Requirements on software components are shown in Figures 4 and 5 for injection and top energy. Again it is clear that constraints and requirements are not the same for a pilot bunch and for 43 bunches or even for 2808 bunches. Initially the SW component core must be available, with

System	Commissioning before beam possible ?	Pilot beam	10^12	43 bunches 1.7 10^12	156 bunches 6 10^12<N<1.4 10^13	936 bunches >5 10^13
Powering interlock system	YES					
Beam interlock system	YES					
Safe distribution of energy	YES					
Safe beam flag	PARTIAL					
Safe distribution of mode	YES					
Safe distr. of squeezing factor	PARTIAL					
Access system	YES					
Vacuum system	YES					
Magnet current change monitor	YES					
BLMs, collimators & apertures	PARTIAL					
BLM in the arcs	PARTIAL					
Collimators and beam absorbers	NO					
Beam position change monitors	NO					
Fast beam current decay monitors	NO					
Transverse feedback	NO					
RF	NO					
Experiments	PARTIAL					
Beam Dumping System	PARTIAL					
TCDQ / TCS	NO					
BPM for BDS	NO					

Figure 3: Table of required interlock clients as a function of the machine commissioning stage for 7 TeV.

System	Commissioning before beam possible ?	First pilot beam	10^12	43 bunches 1.7 10^12	156 bunches 6 10^12<N<1.4 10^13	936 bunches >5 10^13
Post-mortem	PARTIAL					
Software Interlock System	PARTIAL					
Critical settings management	YES					
Sequencer	PARTIAL					

Figure 4: Table of required 'safety' software components as a function of the machine commissioning stage for injection.

a functionality that is a adapted to a given commissioning stage. The Software Interlock System itself hides a large system, with a core to transmit interlocks and a long list of clients: this a an interlock system of its own. A first version of this system is expected to be operational at the SPS for the 2006 machine startup (CNGS commissioning).

Interlock settings

A large effort is put into building a BIS with very high safety standard of SIL3-4. But many interlocks depend on reference and tolerance settings. Some of those settings must be adjustable during operation. Changes of such settings MUST be protected by adequate access control. An uncontrolled modification can be equivalent to MASKING the corresponding interlock.

Front-end frameworks like FESA are presently open and very easy to access, and settings may be changed from any WEB browser at CERN! The separation of technical and general purpose network has improved the situation somewhat but not sufficiently. The development of systems like

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Post-mortem	PARTIAL					
Software Interlock Control	PARTIAL					
Critical settings management	YES					
Sequencer	PARTIAL					

Figure 5: Table of required 'safety' software components as a function of the machine commissioning stage for 7 TeV.

MCS (Management of Critical Settings) to provide (reasonably) safe and controlled access to critical interlock settings is essential for safe operation of the LHC machine protection system.

First pilot at 450 GeV

From a pure DAMAGE protection point of view there is no need of the BIS and its clients for the first injections. Only an interlock on the SPS beam intensity is required.

Some key inputs of the beam interlock system will be tested and ready to go before first beam in the LHC: the Beam Interlock System and some of the key beam interlock clients (Vacuum, Access, Powering interlock system, Dump system, critical BLMs, Experiments) that are not maskable. Those inputs will be active already for the first injections.

First pilot at 7 TeV

The pilot bunch being at the edge of the damage limit at 7 TeV, the BIS must provide some protection even for a pilot, thus requiring a significant number of inputs. In particular a minimal collimation (primary collimator and absorber) with rough positions must be in place [2]. Beam loss monitors around the collimators must be operational. Orbit control must be available for the TCDQ, since an asynchronous beam dump is possibly the worst event for a pilot (the probability to hit the pilot is of course not very high).

43 bunches

With 43 bunches the stored energy reaches a level that is comparable to what is accelerated routinely in the SPS since many years, but which also requires significant interlocking. At the LHC the aim is to reach such stored energy levels in a short time. The SPS experience shows that one can provoke damage with such beams and at the LHC the price to pay is larger: this is therefore a natural stage where the machine protection system must be in an advanced stage of commissioning proportionally more advanced than beam operation. Systems that may not be required at this stage (to be studied): RF and damper interlocks, fast beam current decay and fast position change monitors.

Ions

The ion beams will profit from a MP system that is already commissioned with protons, at least up to a certain intensity, but the safe-unsafe transition must still be analyzed with ions. It is also necessary to analyze what sub-systems of the MP system must be at least partly recommissioned for ions. More detailed studies on ions are foreseen by the MPWG in 2006.

CONCLUSION

For the first injection of a pilot bunch, no machine protection is required except a limitation of the intensity extracted from the SPS. But the BIS and all non-maskable inputs to the BIS will be ready and (pre-)commissioned.

A beam of 10^{12} p constitutes the safe intensity limit for damage protection at injection.

The damage limit at 7 TeV corresponds to 1% of the damage limit at 450 GeV. A pilot bunch is therefore close to the damage limit at 7 TeV. The MPWG presently assumes that the pilot is possibly safe, but some protection will be required (minimal collimation and BLMs) as soon as the pilot bunch is ramped to 7 TeV.

The majority of the MPS must be operational for 43 bunches 7 TeV for 156 bunches at 450 GeV

It is essential to address the issue of how to manage critical interlock settings.

REFERENCES

[1] V. Kain, *Damage Levels: Comparison of experiment and simulation*, Proc. of the LHC project Workshop 2005, CERN-AB-2005-014.

[2] R. Assmann, these proceedings.